proposal for

A PROGRAM FOR RESEARCH ON A
BOOSTER HEART - AUXILIARY VENTRICLE

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OFFICE OF NAVAL RESEARCH
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by

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HEART RESEARCH AT AVCO-EVERETT RESEARCH LABORATORY

Heart Research at Avco-Everett Research Laboratory stems from an early collaboration between Dr. Arthur Kantrowitz, Director of the Laboratory, and his brother Dr. Adrian Kantrowitz, who is Director of Cardiovascular Surgery at Maimonides Hospital in New York. Combining the points of view of a physicist and a practicing surgeon, they investigated problems of circulatory dynamics and devised some of the techniques now employed in cardiovascular surgery. Several of their studies, directed toward artificial aids to the circulation, have been reported in Proceedings of the Society for Experimental Biology and Medicine (Ref. 1), Archives of Surgery (Ref. 2) and Surgery (Ref. 3).

During the past year, Avco-Everett Research Laboratory, under the direction of Dr. Arthur Kantrowitz, has collaborated with the Surgical Research group at Maimonides Hospital in New York in a series of experiments involving mechanical assistance to the heart (see Ref. 4). Figures 1 and 2 will illustrate the nature of these experiments which have been performed thus far with dogs. The equipment has been developed at AERL using Laboratory facilities and funds.

As the illustrations show, the device (termed a "booster heart") consists of an auxiliary ventricle connected across the arch of the aorta and driven by air pressure in response to electronic signals provided by the heart itself. By operating the auxiliary ventricle in proper phase, the systemic circulation can be maintained with a substantially reduced work load on the heart muscle. Such a reduction in the effort required from the heart should, in the opinion of medical authorities, be effective in a large number of cases of cardiac insufficiency.
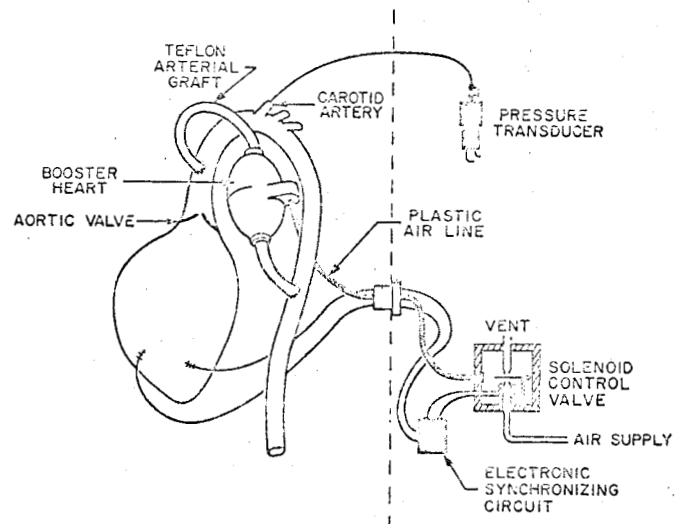
Fig. 1   Booster Heart

Labels in figure: TEFLON ARTERIAL GRAFT, CAROTID ARTERY, PRESSURE TRANSDUCER, BOOSTER HEART, AORTIC VALVE, PLASTIC AIR LINE, VENT, SOLENOID CONTROL VALVE, AIR SUPPLY, ELECTRONIC SYNCHRONIZING CIRCUIT
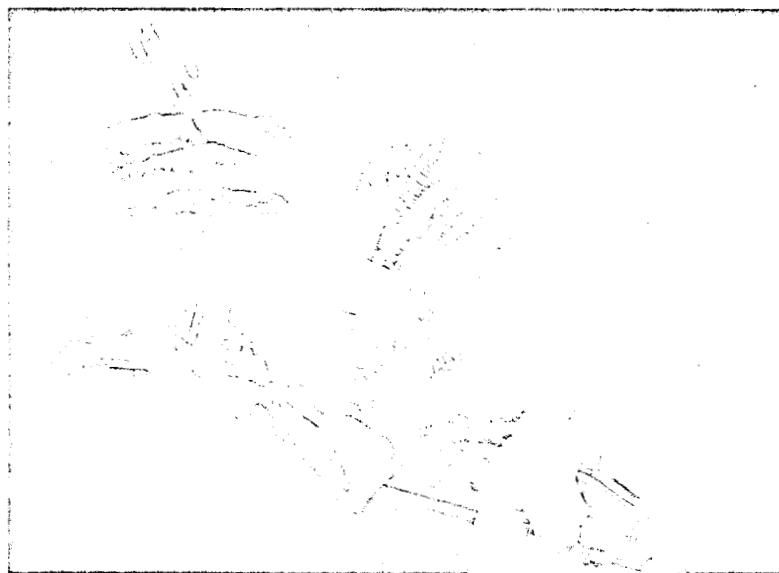

Fig. 2   Experimental Installation of Booster Heart in Dog

The intended operation of the device may be understood by referring to the pressure-pulse diagrams of Figure 3. The pressures shown are those in the left ventricle and also in the aorta near the heart. The upper curves show typical pressures in normal operation of the heart. The contraction of the ventricle distends the aorta and in so doing raises the pressure to about 140 mm Hg. (systolic pressure). When the ventricle starts to relax, the aortic valve closes, maintaining the pressure in the aorta. As the blood flows into the smaller vessels and capillaries, however, the pressure in the aorta drops slowly until the next contraction of the ventricle takes place. Turning now to the operation of the booster heart, it is seen that with the auxiliary ventricle in place, the heart is not required to distend the aorta, but merely fills the auxiliary ventricle, which has much greater compliance than the aorta (or which may be supplied with a negative pressure). Air pressure is then applied to the auxiliary ventricle and the pressure in the aorta is raised to the value required for the systemic circulation. In this way the pressure supplied by the heart need not be greater than the diastolic pressure and the high systolic pressure required to maintain circulation may be supplied artificially by the booster heart.

Figure 4 shows the result of one of a series of 30 or more experiments performed on dogs. The upper curve shown is an oscillogram of the pressure pulses in the left ventricle of the dog's heart. The large drop in amplitude of these pressure pulses shows the effect of operation of the auxiliary ventricle. In this case, the operation of the auxiliary ventricle reduced the work load on the heart by about 28%. The lower curve shows the pressure pulses measured in the carotid artery, near the aorta, with the booster on and off. It will be noted that, while the general level of pressure in the aorta is maintained by
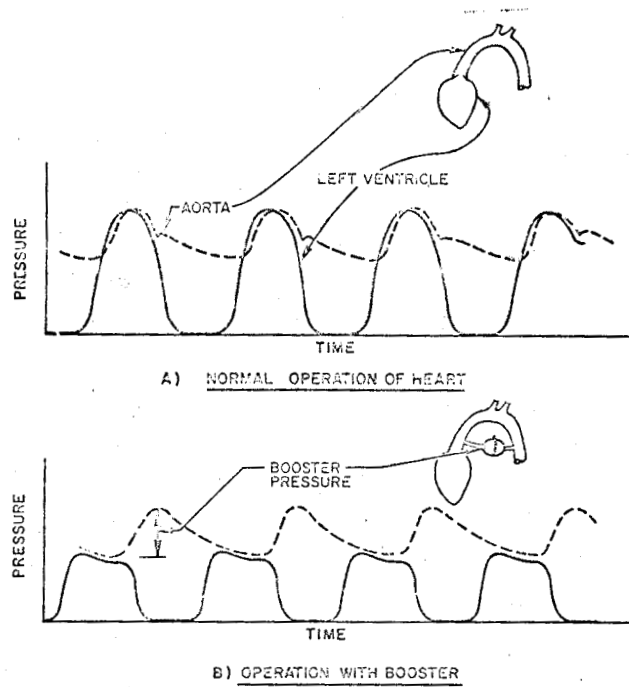
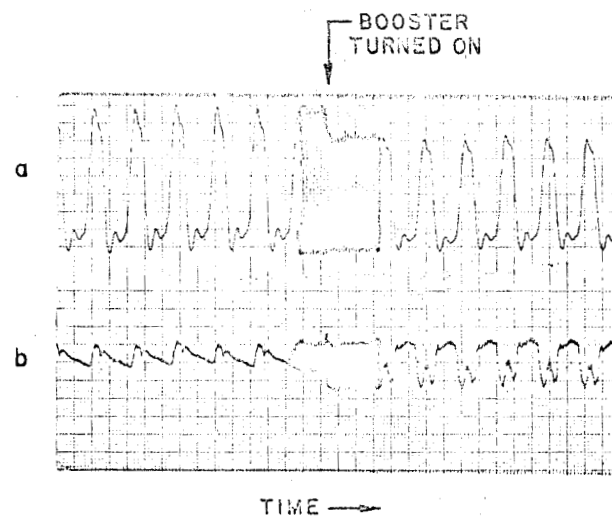Fig. 3   Pressure Wave Forms Illustrating Action of Booster Heart

Fig. 4   Pressure Recordings Showing Operation of Booster Heart in Dog

(a)   Pressure in Left Ventricle
(b)   Pressure in Carotid Artery

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the booster, there are nevertheless sharp fluctuations and the shape of the pulse is not at all like the natural one. In these experiments the booster pressures were supplied in on-off fashion with little attempt to control the wave form. Some control of the wave form may be necessary before the system can be applied to humans.

The determination of a booster system suitable for a human patient must depend on several factors. As is well-known, the pressure pulses supplied by the heart appear in the arterial system as progressive waves. The timing of the impulses supplied by the booster ventricle should thus depend on its position along the artery. Furthermore, the wave form of the pressure pulse changes along the artery, where it is modified by the phenomena of wave reflection and absorption. The form of the pressure pulse supplied by the booster should depend on these factors also. Experimentally, the connection of the auxiliary ventricle across the aortic arch near the heart has given the best results, though the wave form of the arterial pulses observed in the dogs has been considerably modified by the action of the booster.

Some theoretical work on the pulse wave phenomena has already been done at AERL. In this analysis, the blood is considered an incompressible liquid contained in a tube with elastic walls. For sinosoidal waves, long compared with the radius R of the tube, a well-known formula (Ref. 5) gives

$$C^2 = \frac{E\tau}{2\rho R}$$

where C is the speed of propagation, E the elastic modulus of the wall, τ its thickness and ρ is the density of the liquid. For shorter wave lengths λ it is found that

$$C^2 = \frac{E\tau}{2\rho R} \frac{\lambda}{\pi R} \frac{I_1}{I_0}$$

here I_1 and I_0 are modified Bessel functions with the argument $\dfrac{2\pi R}{\lambda}$.

Figure 5 shows the factor of decrease of speed with wave length. For a tube surrounded by a liquid of the same density, we have found a further reduction of speed, given by

$$c^2 = \frac{E\tau}{2\rho R} \frac{\lambda}{\pi R} \frac{I_1}{I_0} K^2$$

where

$$K^2 = \frac{1}{1 + I_1 K_0 / I_0 K_1}$$

and K_0, K_1 are modified Bessel functions. Such an effect simulates the inertial impedance presented by the surrounding tissue on the blood vessel. As Figure 6 shows, the effect of this impedance is to reduce the wave speed by the factor $\dfrac{1}{\sqrt{2}}$ for very short waves.

Calculations such as the foregoing are useful in interpreting the results of pressure measurements made at different points in the arterial system. For controlled experiments on these dynamic phenomena, one would like to have available a dynamically similar model of the circulatory system. Figure 7 illustrates a model we have considered which should reproduce approximately the flow phenomena in the vicinity of the auxiliary ventricle and the main artery. Calculations of the pulse-wave velocity indicate that commercially available rubber tubing would be suitable. The impedance presented by the capillary beds may be taken as primarily resistive, at least on a sufficiently short time scale, and we have assumed that boxes filled with a sponge like material would represent this effect.

We believe that the connection of the auxiliary ventricle across the aortic arch, which results in some unidirectional flow, limits the possibility
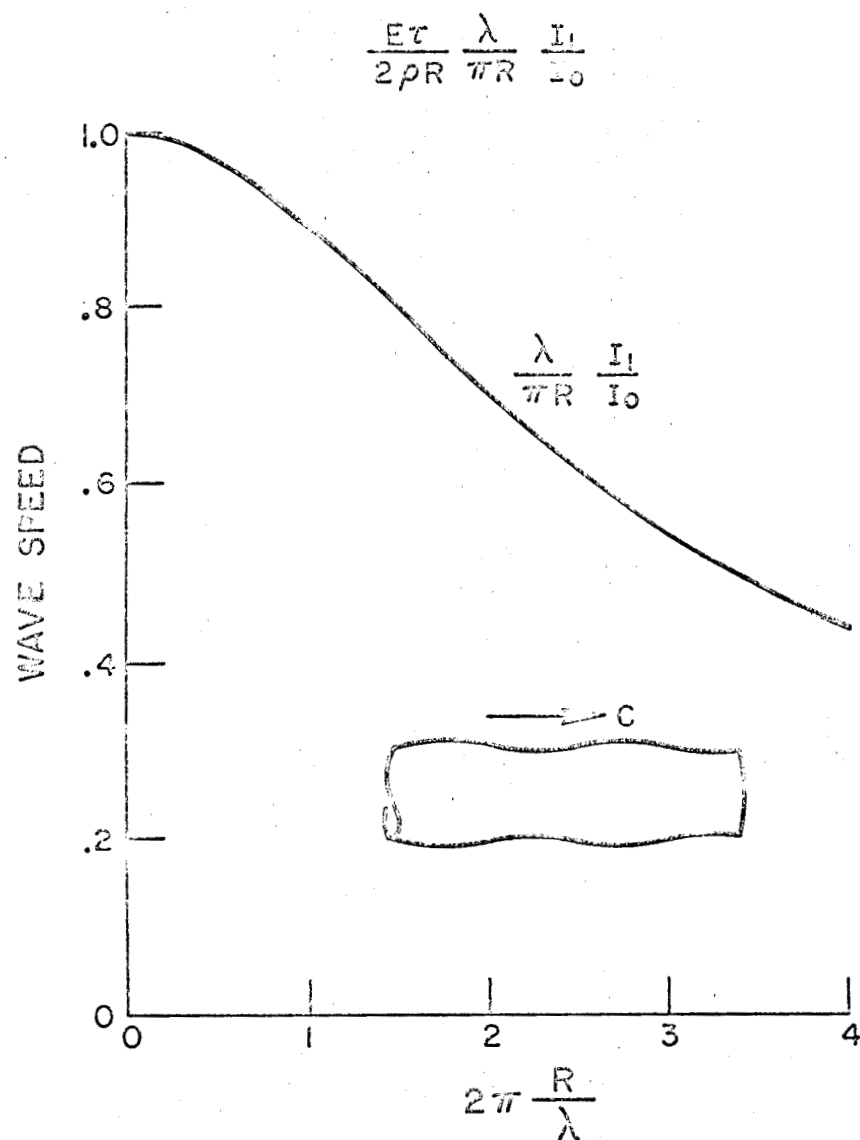
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Fig. 5   Influence of Wave Length λ on Propagation Speed in an Elastic Tube

$$c^2 = \frac{E\tau}{2\rho R} \frac{\lambda}{\pi R} \frac{I_1}{I_0} K^2$$

$$K = \frac{1}{\sqrt{1 + \frac{I_1 K_0}{I_1 K_0}}}$$
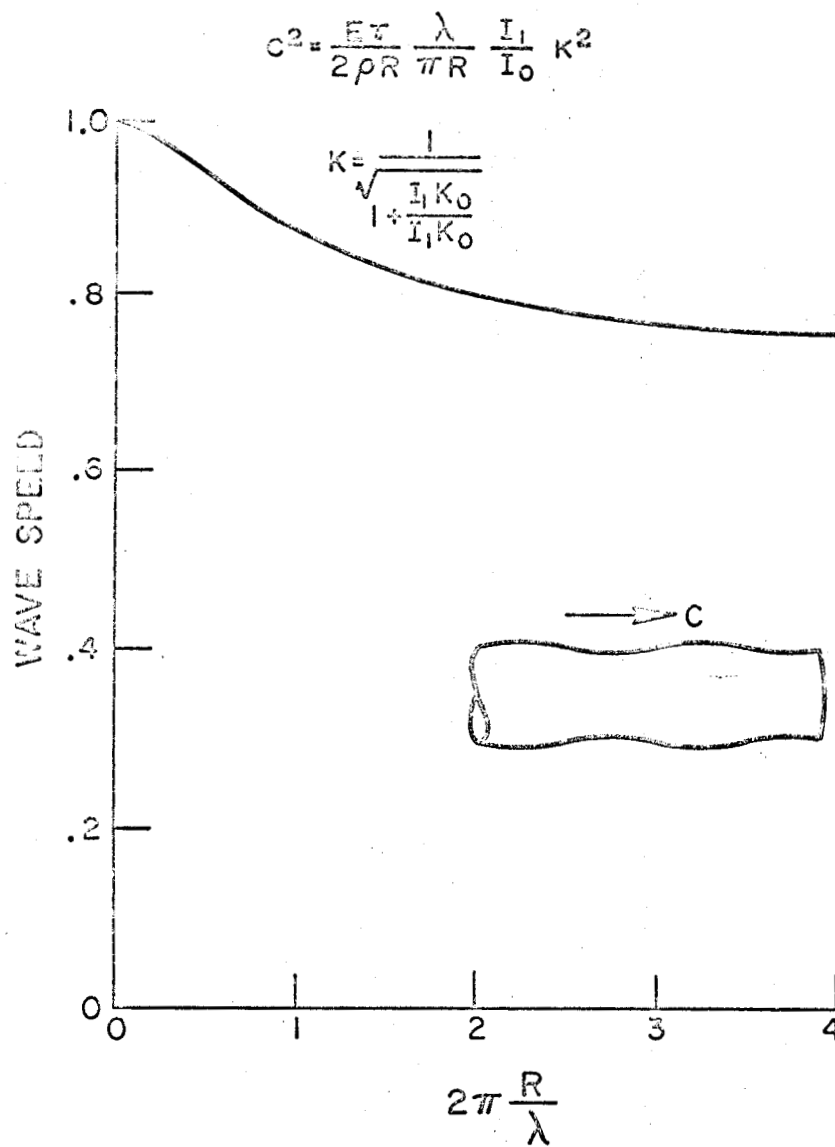
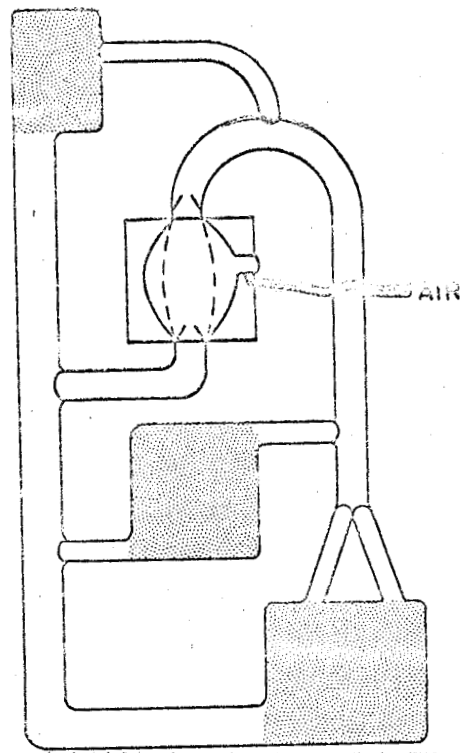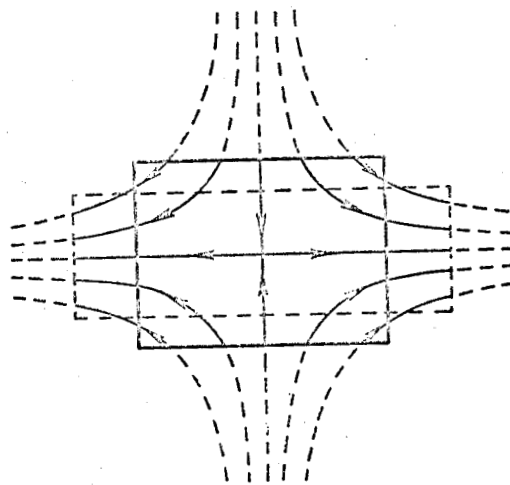Fig. 6   Influence of Surrounding Liquid on Wave Speed in an Elastic Tube

Fig. 7   Circulation Model

$$\phi_2 = R^2 P_2 (\cos \theta)$$

Fig. 8   Flow in a Collapsing Cylinder

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of clotting. In some instances, however, clotting has occurred, probably associated with regions of slow flow within the bulb. As an aid in understanding this phenomenon, we have made some preliminary studies of the potential flow inside an expanding and contracting bulb. Omitting viscosity, we consider time dependent flows represented by

$$\phi(x, y, z, t) = f(t) \varphi(x, y, z)$$

where ϕ is the velocity potential. For the spatial dependence we assume

$$\varphi = \Sigma A_n R^n S_n \qquad \text{where} \qquad R = \sqrt{x^2 + y^2 + z^2}$$

and the S_n are spherical harmonics (see Ref. 6). The motion of the bulb will be represented by that of a moving surface convected with the fluid, i. e. if $B(x, y, z, t) = 0$ is the equation of the bulb surface, then $B_t + uB_x + vB_y + wB_z = 0$. That such a series of spherical harmonics is indeed suitable for the contracting bulb problem is shown by the fact that its first term alone gives a rough approximation to the phenomenon. For this term we have

$$\varphi_2 = R^2 P_2(\cos \theta) = 2x^2 - y^2 - z^2$$

$$\text{or} \qquad \varphi_2 = 2x^2 - r^2$$

This flow satisfies the boundary condition of a circular cylinder with diminishing radius $\left(\dfrac{dr}{dt} = \dfrac{d\varphi}{dr} \right)$, and with uniform flow out the ends. (See Fig. 8). Such formulas should enable us to determine the inertial impedance of the ventricle, though they do not contain such factors as turbulence or viscosity. We feel that such hydrodynamic studies may contribute to the understanding of circulatory phenomena and we would like to continue them.

Of course, the internal parts of the booster system must have a high degree of reliability. A critical item here is the auxiliary ventricle itself, which must expand and contract 30 million times a year without fatigue. In

the dog experiments, a simple Silastic bulb has been used; however, one such bulb failed after two months during a life test we conducted. We are at present investigating forms for stress-free shells and diaphragms and hope to continue life tests on these.

Finally, we have the problem of rational design of a compact external energy supply and servo mechanism. We have experimented with an electrical system employing a motor driven air pump. At present, we are beginning to experiment with an actuator energized by a bottle of compressed gas. We feel that this, together with the associated electronic synchronizing circuit, are primarily engineering problems, though some research effort may be stimulated by them.

While the experiments conducted thus far have shown a considerable measure of success, they have also revealed a number of problems that must be solved before such a system can be employed with human patients.

Specifically, we would like to obtain support for the following items of our program:

1) Theoretical and experimental studies of the pressure wave forms in an elastic arterial system and the effect of the action of an auxiliary ventricle on these pressures.

2) Hydrodynamics of flow within artificial ventricles of various forms.

3) Studies of stresses and fatigue properties of bulbs or diaphragms suitable for artificial ventricles.

4) Research problems that may arise in connection with the design of an external energy supply and servo mechanism.

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COST PROPOSAL

The costs and schedules contained herein are predicated upon the following:

1. A standard CPFF type contract covering a period of performance of twelve (12) months from receipt of a fully executed contract.

2. The use on a no-charge, non-interference basis of the facilities acquired or to be acquired, by the Contractor under Contract AF 33(600)-32006:

    Issuing Office - Headquarters, AMC, Wright-
    Patterson Air Force Base, Ohio
    Administrative Contracting Officer - Mr. J.J. Sullivan
    c/o Research and Advanced Development Division
    Avco Corporation
    201 Lowell Street
    Wilmington, Massachusetts
    Telephone - OLiver 8-8911, Extension 2214

The cognizant Government Auditor for the Avco-Everett Research Laboratory is:

    Captain C. L. Mathews
    c/o Research and Advanced Development Division
    Avco Corporation
    201 Lowell Street
    Wilmington, Massachusetts
    Telephone - OLiver 8-8911, Extension 2726

Inquiries concerning this proposal should be directed to Mr. W. J. Mowbray at DUnkirk 9-3000, Extension 69.

COST SUMMARY

	Man Months	Estimated Cost	
Direct Material			$ 1,000
Direct Engineering Labor			31,051
Principal Research Scientist/Engineer	9	$13,383	
Senior Scientist/Engineer	6	6,174	
Technician	18	9,576	
Machinist	1	581	
Support Direct Labor		1,337	
Engineering Overhead			31,362
Travel and Subsistance			1,306
Total Prime Cost			$64,719
General and Administrative Expense			5,178
Total Cost			$69,897
Fixed Fee			6,980
TOTAL			$76,877

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    Artificial Left Heart to Permit Surgical Exposure of Mitral
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